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University of Alabama in Huntsville (UAH)
April 15-17, 2003

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Welcome and Introduction to ASPW 2003

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Welcome to the 14th NASA-MSFC-JPL Advanced Space Propulsion Workshop (ASPW2003), Tuesday, April 15, through Thursday, April 17, 2003, at the University of Alabama, Huntsville Alabama. The emphasis of the Workshop is on low Technology Readiness Level (TRL), e.g., TRL=1-3, relatively far-term space propulsion and power concepts and technologies that hold the promise of enabling ambitious robotic and human exploration missions of the 21st century. (For reference, a list of TRL definitions is given below.) One of the main goals of the Workshop is to provide an informal forum for information exchange and program coordination between researchers in low TRL advanced space propulsion. A second major goal is to identify major research issues and potential benefits for each long term enabling technology and the effort (manpower and facilities) needed to develop this technology, as well as the "best guess" as to the prospects of developing this technology. To this end, the workshop will include a discussion/roadmapping exercise at the end of each technology session to assist NASA program managers in implementation of promising technologies.

NASA Technology Readiness Level (TRL) Definitions

Category	Level	Qualifier/Development Hurdle
Basic Research	1	Basic scientific/engineering principles observed and reported.
Feasibility Research	2	Technology concept, application, and potential benefits formulated (candidate system selected).
Feasibility Research	3	Analytic and/or experimental proof-of-concept completed (proof of critical function or characteristic).
Technology Development	4	System concept observed in laboratory environment (breadboard test).
Technology Development	5	System concept tested and potential benefits substantiated in a controlled relevant environment.
System Development	6	Prototype of system concept is demonstrated in a relevant environment.
System Development	7	System prototype is tested and potential benefits substantiated more broadly in a relevant environment.
Operational Verification	8	Actual System constructed and demonstrated, and benefits substantiated in a relevant environment.
Operational Verification	9	Operational use of actual system tested, and benefits proven.

NASA's In-Space Propulsion Program

Les Johnson
NASA Marshall Space Flight Center

In order to implement the ambitious science and exploration missions planned over the next several decades, improvements in in-space transportation and propulsion technologies must be achieved. Future missions will require 2 to 3 times more total change in velocity over their mission lives than the NASA Solar Electric Technology Application Readiness (NSTAR) demonstration on the Deep Space 1 mission. New opportunities to explore beyond the outer planets and to the stars will require unparalleled technology advancement and innovation.

Chemical propulsion, which relies on making chemical bonds to release energy and produce rocket exhaust, has been the workhorse of space exploration since it's beginning. However, we have reached its performance limits and those limits are now hindering our continued exploration of space. The efficiency with which a chemical rocket uses its fuel to produce thrust, specific impulse (I_{sp}), is limited to several hundred seconds or less. In order to attain the high speeds required to reach outer planetary bodies, much less rendezvous with them, will require propulsion system efficiencies well over 1,000 sec. Chemical propulsion systems cannot meet this requirement.

NASA's In-Space Propulsion (ISP) Program is investing in technologies to meet these needs. The ISP technology portfolio includes many advanced propulsion systems. From the next generation ion propulsion system operating in the 5 - 10 kW range, to advanced cryogenic propulsion, substantial advances in spacecraft propulsion performance are anticipated. Some of the most promising technologies for achieving these goals use the environment of space itself for energy and propulsion and are generically called, "propellantless" because they do not require on-board fuel to achieve thrust. Propellantless propulsion technologies include scientific innovations such as solar and plasma sails, electrodynamic and momentum transfer tethers, and aeroassist and aerocapture. An overview of both propellantless and propellant-based advanced propulsion technologies, and NASA's plans for advancing them, will be provided.

Overview of the NASA MSFC Propulsion Research Laboratory

Steve Rodgers
NASA Marshall Spaceflight Center
Huntsville Alabama

Overview of the NASA University Research Engineering Technology Institute (URETI)

Michael M. Reischman
NASA HQ

Overview of the University of Alabama Huntsville Propulsion Research Center

Clark Hawk
University of Alabama Huntsville

Overview of the Pennsylvania State University Propulsion Engineering Research Center (PERC)

Robert J. Santoro, Director and Guillet Professor of Mechanical and Nuclear Engineering
Sibtosh Pal, Associate Director
Roger Woodward, Associate Director

The Propulsion Engineering Research Center at Penn State was established in August 1988 as a NASA University Space Engineering Research Center (USERC). The program had a fixed length of support with the intention to develop centers of excellence that would be self-sustaining in terms of funding. Following the USERC support, PERC has evolved into a self-sustaining entity that is funded at nearly 4 million dollars in annual external research support. Propulsion-related research efforts by faculty associated with PERC include rocket, gas turbine, and internal combustion engine projects as well as efforts in microwave and propellantless propulsion.

Since its inception in 1988, PERC has graduated nearly 200 M.S. and Ph.D. students, approximately 75% of whom are employed within industry, government laboratories, and academia in jobs directly related to propulsion.

Major aerospace propulsion research facilities at PERC include the Cryogenic Combustion Laboratory (R. J. Santoro), High Pressure Combustion Laboratory (K. K. Kuo), Turbulent Combustion Laboratory (D. Santaviccca), CFD parallel computing PC cluster (500 nodes) (V. Yang), Micro Power and Propulsion Research Laboratory (R. Yetter), Aerospace Engineering Propulsion Laboratory (M. M. Micci), and an Electron Beam – Physical Vapor Deposition (EB-PVD) facility (J. Singh).

Over the past decade PERC has been involved in a number of forefront propulsion research initiatives including NASA Reusable Launch Vehicle efforts in which gas–gas injector, oxygen-rich preburner and tripropellant concepts were investigated. Studies of the rocket ejector mode of the Rocket-based Combined Cycle (RBCC) engine concept were initiated several years ago and are still on-going. Recently work in air-breathing Pulse Detonation Engines (PDEs) has been extended to Pulse Detonation Rocket Engines in collaboration with Pratt & Whitney.

In addition to the RBCC studies, currently funded aerospace propulsion projects include combustion experiments to support CFD validation and injector optimization for full-flow staged combustion cycle engines, experimental and analytical studies of supercritical injection and combustion, combustion studies of thermally stable coal-derived jet fuels, gas-turbine combustion stability and active-control studies, and PDE-ejector thrust augmentation. PERC is teamed with UAH, UTSI, Purdue, Auburn, and Tuskegee in a major effort funded by the NASA Next Generation Launch Technology Program to develop technology for robust long-life combustors. In this effort, PERC is attacking combustion instability issues for future engines.

In-house-developed CFD codes ranging from Direct Numerical Simulations (DNS), Large Eddy Simulations (LES) , and lower order models with turbulence closure and variable thermophysical properties are being applied to propulsion problems in parallel with experimental efforts. The latter techniques are being applied to full system (inlet to nozzle) simulations of multicycle PDEs, gas-turbines, and scramjets. DNS is applied to small-scale reacting flow-fields while LES is applied to unsteady, variable-property, multi-phase combustor flowfields.

Advanced space propulsion activities at PERC include low-power, high-specific-impulse microwave thruster research, meso- and micro-scale thruster research for small spacecraft that require low thrust values (~mN) and low impulse bits (~10 mN-s), and electrodynamic tether research which focuses on current collection processes and spacecraft-plasma interactions. Three-dimensional Direct Simulation Monte Carlo methods are applied to microthruster performance analysis to accurately predict micro-scale flows. An overview of selected space propulsion projects will be presented.

Overview of the Project Prometheus Program

Garry Burdick
NASA JPL

This presentation will give an overview of the Project Prometheus Program (PPP, formerly the Nuclear Systems Initiative, NSI) and the Jupiter Icy Moons Orbiter (JIMO) Project (a component of PPP), a mission to the three icy Galilean moons of Jupiter.

The Project Prometheus Program as approved in the FY 2003 Federal Budget has three components: Nuclear Power, Nuclear Propulsion Research, and the JIMO Project.

The Nuclear Power component will develop the next generation of multi-use radioisotope power systems and sponsor advanced research in power conversion technologies best suited for this scale of power supplies for deep space and planetary surface exploration applications (generally operating at less than a few hundred watts in a vacuum or in a range of atmospheres found within the Solar System, such as on the surface of Mars).

The Nuclear Propulsion Research component will sponsor research into advanced fission-reactor-powered electric propulsion systems with an emphasis on breakthrough reactor, power conversion, and electric propulsion technologies. Other nuclear propulsion technologies would also, in the future, be explored, such as nuclear thermal propulsion, that could play a role in the human exploration of Mars.

The JIMO Project component is both a proposed mission to Jupiter that would demonstrate the unprecedented capabilities provided by nuclear electric power and propulsion systems (high maneuverability as well as ample power for a new generations of science investigations and high-speed communications), and at the same time, enable achievement of high-priority science at all three of the icy Galilean moons of the Jovian system: Callisto, Ganymede, and Europa. These moons are believed to contain vast oceans under their surfaces that could harbor conditions conducive to life.

NASA Institute for Advanced Concepts - Relationship to NASA Advanced Propulsion Program

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The NASA Institute for Advanced Concepts (NIAC) is sponsored by NASA HQ to inspire, solicit, review, select, and nurture revolutionary advanced concepts leading to the infusion of the most promising aeronautics and space candidates into NASA. NIAC has funded concepts that explore the possibilities of significant breakthroughs and paradigm shifts applicable to the exploration of space. In its first five years of operation, NIAC has funded over 100 studies, examining systems and architectures that look ahead ten to forty years. This paper addresses the relationship of NIAC studies to the NASA Advanced Propulsion Program.

Findings of the NASA Breakthrough Propulsion Physics Project

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As its name suggests, the Breakthrough Propulsion Physics Project is specifically looking for propulsion breakthroughs from physics. It is not looking for further refinements of existing propulsion and power technology. No matter how advanced in technological embodiment, rocket physics is fundamentally inadequate for interstellar distances. The only way to surpass these limits is to discover better propulsion physics. From 1996 to 2002, this Project sponsored a modest variety of approaches toward this end, and also developed a process to credibly proceed on such a risky and high-gain topic. This presentation will summarize the findings and methods of this Project, including lessons learned from the following research tasks:

- Problem definition for "space drives"
- Independent assessment of transient inertia observations
- Experimental and theoretical assessments of quantum vacuum energy
- Experimental tests on a tortional theory of electromagnetism
- Experimental investigations of superconductor-gravity claims
- Experimental and theoretical assessments of amplified quantum tunneling
- Theoretical assessments of Deep Dirac energy transitions
- Experimental test of Schlicher's thrusting antenna
- Experimental and theoretical assessments of Heaviside force

Advanced Chemical and Earth-to-Orbit (ETO) Propulsion

- Advanced High Isp Chemical Propellant Engines for Air-Launched Rockets, Benjamin Donahue (Boeing Phantom Works)
- Metallic Hydrogen-The Rocket Fuel of the Future: Can it be Made? Is it Metastable?, Isaac F. Silvera (Harvard U.)
- Electromagnetic Launch Assist and "Virtual Staging" for an Efficient All-Rocket RLV, Gordon Woodcock and John Suter
- Implementation of Magnetohydrodynamic Energy Bypass Process for Hypersonic Vehicles - Status Report, Ying-Ming Lee et al. (MSE Tech. Appl., Inc.)
- Experimental Demonstration of Magneto-Hydrodynamic (MHD) Acceleration - A Progress Report, Unmeel B. Mehta et al. (NASA Ames)
- MHD Augmented Propulsion Research and Experiments – Current Status, Harold J. Schmidt et al. (LyTec LLC)
- MHD Augmentation of Chemical Rockets Revisited with Advanced Magnet and Rectenna Technology, James N. Chapman, et al. (LyTec, LLC)
- Discussions

Advanced High Isp Chemical Propellant Engines for Air-Launched Rockets

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This paper presents performance figures for high Isp, advanced chemical propulsion rocket stages launched from large transport aircraft, including the Boeing 747, the large Russian Antonov An-226 transport, and two other higher capacity, conceptual carrier aircraft. The 747-400F has a sizable lift capability; it can carry a cargo of 315,000 lb mounted externally in a piggyback arrangement to an altitude of 30,000 ft and a speed of Mach 0.75. Results show, however, that a reusable rocket of 315,000 lbs could deliver a significant payload to low Earth orbit only by utilization of a propellant with a significantly higher specific impulse than that attainable by an oxygen and hydrogen engine. This analysis presents rocket designs utilizing advanced fluorine-lithium-hydrogen engines, engines which have been tested at both Sea-level and altitude conditions in the past with good success, achieving a vacuum specific impulse of 523 s - the highest ever demonstrated by a chemical rocket engine, and almost 70 s higher than that of the Space Shuttle Main engine. A 747 based, reusable air launched rocket with a 523 s specific impulse could deliver a 8,000 lb payload pod to orbit. Advantages of air-launch include a reduced ascent-to-orbit delta-velocity, reduced drag incurred by rocket flight beginning at an atmospheric density one-third that at sea level, and less stressing ascent loads. Also presented are ascent delta-velocity requirements for several altitude and Mach number start conditions and information on fluorine engine history.

Metallic Hydrogen-The Rocket Fuel of the Future: Can it be Made? Is it Metastable?

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Lyman Laboratory of Physics
Harvard University

Atomic hydrogen is the lightest element and as such has great potential as a high Isp propellant. A sample of hydrogen stabilized in the solid atomic form as metallic hydrogen is calculated to have an Isp of 1400 sec, far exceeding the 454 sec of LOX/LH2. Atomic metallic hydrogen is also the dream material of a physicist, predicted to be a room temperature superconductor, with possible exciting properties such as being a fluid at zero Kelvin due to its large quantum mechanical zero-point motion. At ambient pressure and low temperature (below 14 K) hydrogen condenses as a molecular solid. Wigner and Huntington predicted almost 70 years ago that it will transform to the metallic atomic form at a pressure of a quarter of a megabar. Their prediction has been far exceeded; hydrogen is still molecular at 3 megabar. Early on metallic hydrogen was predicted to be metastable, as diamond is a metastable form of carbon. That is, if it is produced at high pressure and the pressure released, it will stay in the metallic phase. On the other hand there are calculations that suggest a short lifetime due to quantum mechanical tunneling to the molecular state. Tunneling calculations have large uncertainties in the lifetime. To answer these questions metallic hydrogen must be made in the laboratory.

Using diamond anvil cells, megabar pressures can be achieved on hydrogen. In this pressure regime it is more than 10-fold compressed in volume. Thus metallic hydrogen not only packs a punch as a rocket fuel, but also requires smaller storage volumes than say liquid hydrogen. If a material is metastable, then there is a potential barrier that prevents it from equilibrating to the ground state. By the same token, this barrier may prevent hydrogen from entering the metallic state until it is pressed to exceptionally high pressures. High temperatures can assist in overcoming barriers to get into an energetically favored state. Continuous heating of hydrogen at high pressure is out of the question as the hydrogen diffuses into the diamonds, embrittles them, and they fail. We are developing pulsed laser heating techniques to heat the megabar hydrogen sample to thousands of degrees Kelvin in nanosecond periods of time. This time should be sufficient to overcome the putative barrier, yet so short that there is no time for the hydrogen to diffuse into the diamond. At this time we have developed a method of measuring the peak temperature in a sample during nanosecond thermal pulses, accurate to of order 10 K at 2000 K. We are now extending this method to high pressures in a diamond anvil cell. Our methods and progress will be discussed.

Electromagnetic Launch Assist and "Virtual Staging" for an Efficient All-Rocket RLV

Gordon Woodcock and John Suter

Reusable launch vehicles have been analyzed by NASA since the early 1960s, and related concepts go back at least to the Saenger "rocket bomber" concept in Germany, 1942. The number of concepts put forward is at least in the hundreds. The only concept fully developed was the space shuttle, which is partially reusable, and has not realized the low-cost promise of reusable systems. A few related flight test vehicles have been flown (X-15) or partially constructed (X-33 and X-34), but the search for a meritorious concept continues. The shuttle experience shows that cost goals for low cost access to space probably require complete reusability.

The concept presented by these authors puts together a number of synergistic previous ideas to derive an all-rocket RLV system design that appears, on initial investigation and analysis, to close technically and to offer highly desirable attributes. This concept was founded on the idea that an almost-workable concept may be made workable, even attractive, by incremental improvements. The main ideas include:

Horizontal takeoff using a ground-based accelerator … dates to the Saenger concept of 1942, and reappeared in various forms as the Boeing RASV, and later in an HRST concept studied by Woodcock. Shown by these studies to offer better performance than vertical takeoff SSTO.

Use of two fuels, hydrogen and kerosene ("dual fuel") to provide "virtual staging" … dates to a concept introduced by Robert Salkeld in the 1970s. Unlike the original Salkeld concept, which invoked a special rocket engine operating on both fuels plus liquid oxygen, the present concept was analyzed based on performance of two existing engines, the RD-180 and the SSME. Dual fuel was shown by Salkeld to improve performance, and is shown to have a payoff here.

Kerosene in wing tanks … long used by airplanes; the Boeing RASV also put propellants in the wings for load relief. Improves the payoff of dual fuel by accommodating the kerosene in volumes in the wings that would otherwise go unused.

The presentation will cover the concept features and benefits, describe the air vehicle and accelerator concepts, and present performance and mass estimates. A discussion of flight safety and its accommodation is included. Ground accelerator sizing and levitation trades are discussed. Cost drivers for rocket and airbreather approaches are compared.

Implementation of Magnetohydrodynamic Energy Bypass Process for Hypersonic Vehicles – Status Report

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The global political structure has changed dramatically since the breakup of the former Soviet Union, and world changes have caused the United States to reprioritize its national hypersonic needs. The U.S. Government has looked at the needs of the future, and the hypersonic aerospace plane is one of the systems included in alternative force structures. One hypersonic aerospace plane concept would involve magnetohydrodynamic (MHD) technology (i.e., the AJAX hypersonic flight vehicle concept) originally proposed by Russian scientist Vladimir Fraishtadt.

This paper reports on the current progress and findings of an air-breathing horizontal takeoff and landing design concept using an MHD energy bypass injector ramjet engine being studied at MSE Technology Applications, Inc. (MSE), HyperTech Concepts, and several universities for the National Aeronautics and Space Administration Langley Research Center (NASA-LaRC) under a Phase II Small Business Innovation Research (SBIR) project. The areas that are addressed in this paper include: 1) ionization required to achieve the required energy bypass, 2) utilization of a nonequilibrium model to calculate nonequilibrium engine ionization conditions, 3) hydrocarbon fuel reforming, and 4) vehicle performance and sizing. A quasi-one-dimensional (1-D) electromagnetic code combined with a new scramjet model, as well as other tools, were used to examine total system performance.

Experimental Demonstration of Magneto-Hydrodynamic (MHD) Acceleration - A Progress Report

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The electrical power generation has successfully been achieved by magneto-hydrodynamic (MHD) means. However, relatively few experiments have been made to date for achieving gas acceleration by the MHD means. MHD acceleration has several potential applications. It can improve the performance of hypersonic scramjet engines for space access and hypersonic cruise vehicles, of high enthalpy ground-based test facilities, and of chemical rocket engines for in-space propulsion.

The most important aspects of the planned research program are the measurement of flow acceleration and Joule heating in the channel with special attention 1) to shorting in the boundary layers parallel to the current due to locally high load factors and 2) to energy loss in the perpendicular boundary layers due to cathode and anode fall heating. Herein, sample results obtained thus far are presented.

The MHD channel is supplied with flow from an electric-arc shock tube though a supersonic nozzle 0.528 cm wide. The shock tube is operated with 53.2% N_2O, 46.8% N_2 mixture at a nominal fill pressure of 7.5 Torr. The nozzle reservoir pressure is ~9.0 atm. The driven tube is seeded with 2 - 3 micron particle diameter K_2CO_3 powder to a concentration of ~1% K by mass. The MHD channel is 24.1 cm long, 2.03 cm wide and its height varies from 1.39 cm at the first electrode pair to 2.00 cm at the last electrode pair. There are 19 electrode pairs, of which the first 17 are powered and the last electrode pair is used to measure the velocity achieved by means of the back EMF generated by the flow in the magnetic field. The channel Mach number varies from 2.0 to 2.5. The nominal shock velocity is 3.0 km/sec. The channel static pressures decrease from ~0.6 atm at the channel entrance to ~0.4 atm at the channel exit.

The MHD channel diagnostics include current and voltage measurements. Floating potential measurements are made in the channel sidewall to determine the true conductivity. Static pressure measurements are made at five locations along the channel. Additionally, impact pressure measurements are made at the channel exit, using a four-headed pitot rake.

Nine MHD acceleration tests, with voltages applied to the capacitors powering the channel electrodes ranging from 210 to 380 V, were conducted. Two tests with magnetic field, but with the electrodes unpowered, were conducted. Two conductivity tests without magnetic field and with only three electrode pairs powered were also conducted. A spectroscopic temperature measurement system based on the potassium D lines at ~760 nm is being developed.

The shock velocities ranged from 2.95 to 3.04 km/sec, and the mean magnetic field was 0.92 Tesla. The test times varied from 670 to 870 microseconds. The measured currents ranged from 20 to 50 A per electrode pair; and the total voltage across the various electrode pairs ranged from 120 to 150 V. The maximum electrical power input was ~127 kW. The MHD channel operated in the Faraday mode, developing Hall voltages of ~300 V along the length of the channel. The conductivity for the MHD tests ranged from 0.95 to 1.45 Mhos/cm. The tests without magnetic field produced conductivities of 1.5 to 2.0 Mhos/cm. In the back EMF tests, the EMFs ranged from 26 to 44 V along the length of the channel.

The total cathode and anode sheath and boundary layer voltage drops were 68 - 80 V, and applied voltages across the central part of the flow in the channel ranged from 42 to 80 V. Pitot pressure measurements indicate momentum increases of 10 to 24%. The EMFs generated at the last electrode pair indicate velocity increases of 15 to 38%.

MHD Augmented Propulsion Research and Experiments – Current Status

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Ron J. Litchford and John W. Cole
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Crossed field magnetohydrodynamic (MHD) accelerators have long been advocated and utilized in hypervelocity ground test facilities. The MHD accelerator, by direct enhancement of the working plasma velocity, can augment the plasma total enthalpy without the necessity of confining and expanding a plasma from a high temperature and high-pressure reservoir. The fundamental constraint of the acceleration process is that plasma has a sufficient electrical conductivity. Seeding of hot plasma with easily ionized alkali metal salts allows a variety of plasma sources including chemical combustors and arc heaters to be used as the plasma source for an accelerator.

The same acceleration process that is used in a ground test facility for producing a hypervelocity flow environment can be incorporated as a thrust augmentation in a propulsion environment. Such an accelerator has the effect of increasing the plasma velocity, or equivalently, the specific impulse of the propellants in the case of a combustion driven system.

A small MHD accelerator test bed has been designed for the NASA Marshall Space Flight Center and is described in the paper. This facility utilizes a 1.5 MWe arc heater as the working plasma source and a 2MWe MHD accelerator. Figure 1 provides a schematic view of the facility and Figure 2 is a photograph of the recently fabricated MHD accelerator to be installed in the test bed. The MHD accelerator is designed as and externally diagonalized segmented heat sinked channel. A 2 Tesla iron frame magnet, previously used for commercial MHD base load power studies, will be used for the accelerator magnetic field. The design and potential use of the facility in progress is discussed.

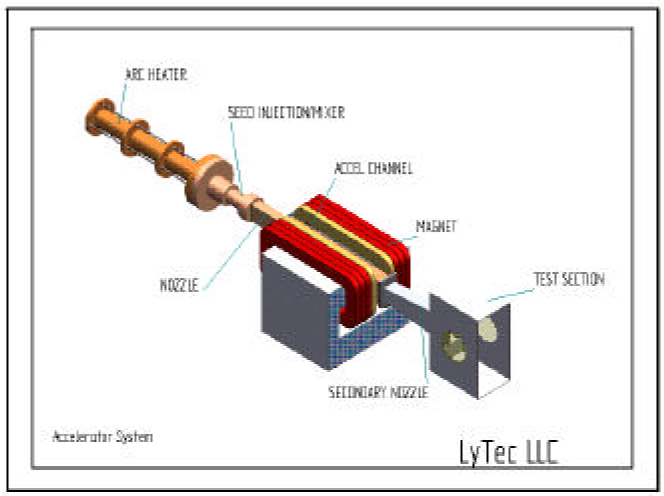

Figure 1. Schematic of MHD Accelerator Propulsion Experimental Apparatus

Figure 2. MHD Accelerator Channel – Hardware Item

MHD Augmentation of Chemical Rockets Revisited with Advanced Magnet and Rectenna Technology

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Previous studies of MHD augmentation of chemical rocket engines to achieve much higher Isp (up to about 2,500 seconds) using beamed electrical power have found that the weight of the equipment added, primarily the magnet and the rectenna, severely limit the advantageous application range. Currently, NASA is studying the application of carbon nanotubes for use both as conductors having current density several orders of magnitude higher than conventional superconductors and having strength to weight ratios about 100 times that of stainless steel. This technology promises to reduce the magnet weight so dramatically that it is virtually negligible. In addition, recently reported work in Canada on microwave rectennas for beamed power promise power densities 20 MWe/kg. When these two developments are ready for implementation, the regime of fruitful application of MHD augmentation is greatly expanded.

This presentation includes the current status of the LyTec NASA contract to investigate the application of carbon nanotubes to space based and airborne magnets. In addition, it will present the impact on our previous study results of successful development of the carbon nanotube magnet and the application of the lightweight microwave rectennas.

Discussions

Advanced Chemical and Earth-to-Orbit (ETO) Propulsion

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- MHD Augmentation of Chemical Rockets Revisited with Advanced Magnet and Rectenna Technology, James N. Chapman, et al. (LyTec, LLC)

Discussions (All)
- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Propulsion Component Improvements

- Compact High-Voltage Pulsed Power Source for Micropropulsion and Fast Electro-Optic Switching, N. Kukhtarev et al. (Physics Department, Alabama A&M University)
- Flight-Weight Power Supplies for Superconducting Magnets, Roy G. Goodrich (Louisiana State U.)
- Discussions

Compact High-Voltage Pulsed Power Source for Micropropulsion and Fast Electro-Optic Switching

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Photovoltaic (or giant photovoltaic) effect is relatively new transport phenomenon: generation of high voltage (~100 kV) in a homogeneous noncentrosymmetric (mostly ferroelectric) materials under homogeneous illumination. Closely related phenomenon of ferroelectric electron emission (FEE) is now intensively investigated world-wide due to potential applications in particle-beam and plasma physics.

In our experiments we have observed photoinduced generation of high-voltage electrical pulses in the ferroelectric crystals LiNbO3:Fe during continuous illumination by low-power visible light (~100mW). This effect was observed with incoherent or with coherent (laser) illumination. Depending on ambient-gas condition and electrode configuration, electrical pulses may be bipolar or unipolar with average width about 10 micro-sec and repetition rate in parts of a second. Maximal instant current was about 50μA and the shortest pulses were in nanosecond range.

We have successfully tested this photo galvanic pulsed power source for electro-optic switching, using standard electrooptic modulator. We have observed also actuation of the mechanical movement of the crystal (with mass of crystal 6.8 g), correlated with electrical pulses generation. We suggest a physical model of generation of electrical pulses, based on combined effect of photo galvanic, thermo galvanic and surface-air plasma formation. In on-going experiments we investigate optimal conditions for utilization of observed trust-like forces for applications in micro propulsion. [1,2]

1. N.Kukhtarev, T.Kukhtareva,D.Frazier, B.Penn, J.Wang, M.Bayssie, “Actuation of mechanical movement of a microscopic crystal by low-power CW laser”, CLEO’2003, Technical Digest

2. N.Kukhtarev, T.Kukhtareva, M.Edwards, B.Penn,D.Frazier et al, Journ. Nonlinear Optical Physics&Materials, Vol.11,No.4,p1, 2002; Proc.SPIE,Vol.4803.p.281 (2002)

Flight-Weight Power Supplies for Superconducting Magnets

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The development of flight-weight magnets is crucial to a number of advanced propulsion system architectures. For a complete superconducting flight-weight magnet system the weight of the coil, support structure, cryogenics, and the power supply must be taken into consideration. Superconducting magnets that are capable of producing the required fields over a sufficient volume to be useful require charging into operation by currents in excess of 100 amps and 1 kW power making DC power supplies for this purpose involve massive transformers and result in high-weight systems. The design and operation of a flight-weight partially superconducting power supply known as a flux pump will be described.

Discussions

Propulsion Component Improvements

- Compact High-Voltage Pulsed Power Source for Micropropulsion and Fast Electro-Optic Switching, N. Kukhtarev et al. (Physics Department, Alabama A&M University)
- Flight-Weight Power Supplies for Superconducting Magnets, Roy G. Goodrich (Louisiana State U.)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions
- Special Brain Teaser: What are some cross-cutting advanced technologies that could have dramatic impact/benefit on your propulsion technology?
    - Example: lightweight radiators (also resistant to micrometeorite/debris impact)

Beamed Energy Propulsion

- Status of the Water MET at The Aerospace Corporation, Kevin D. Diamant and Ronald B. Cohen (Aerospace Corporation)
- High Average and Peak Power Integrated Laser for Propulsion, Richard L. Fork et al. (U. of Alabama in Huntsville)
- Laser Application for the Control of Satellite Orbits, Anatoliy F. Nastoyashchii (Troitsk Institute for Innovation and Fusion Research, Troitsk, Moscow Reg., Russia)
- Investigation of Plasma Plume Dynamics by ICCD Imaging for Ablative Laser Propulsion, Jun Lin et al. (U. of Alabama, Huntsville)
- Analysis of Two-Pulsed Ablation of Elementary Targets for Ablative Laser Propulsion, M. Shane Thompson et al. (Information Systems Laboratories, Inc.)
- Solar Thermal Propulsion Improvements at Marshall Space Flight Center, Harold P. Gerrish Jr. (NASA MSFC)
- Discussions

Status of the Water MET at The Aerospace Corporation

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Microwave electrothermal thruster (MET) is a term applied to a class of devices which heat propellant through contact with a plasma sustained by absorption of microwave power. One possible MET configuration consists of a resonant cavity applicator, the geometry of which is selected to support a standing wave pattern. At an antinode of this pattern the electric field becomes large enough to cause breakdown of the gaseous propellant. Once breakdown has occurred, the free electrons in the plasma absorb the microwave power very efficiently, and transfer energy to the heavy species through collisions. Propellant heated in this manner is exhausted through a converging-diverging nozzle to produce thrust.

DARPA is developing a space system architecture for power and propulsion based on water. An element of this architecture that is the focus of our research is a low thrust, high specific impulse water rocket. Water's low molecular weight favors an electrothermal device for good efficiency at moderately high specific impulse. An electrodeless discharge is desirable since the dissociation products of water can be corrosive at high temperature.

For approximately two years The Aerospace Corporation has been investigating the performance of a MET using in-vacuum thrust stand measurements. The MET was provided by Research Support Instruments and is based on a Penn State design. The most comprehensive database to date of direct measurements of thrust, specific impulse, and thrust efficiency was compiled for helium and nitrogen at powers near 1 kW. Following this investigation, the MET was modified for higher power operation and a system for delivering a known mass flowrate of water vapor was constructed. Subsequent operation with high pressure water plasmas at powers from 2 to 4 kW resulted in measured thrusts from 100 to 250 mN and specific impulses from 300 to 400 seconds, with a peak measurement of 428 seconds [1].

The purpose of this talk will be to acquaint the audience with MET technology and with The Aerospace Corporation's efforts to develop a water MET. We will also describe our most recent experiments on the influence of nozzle position and geometry on performance, and our current effort to incorporate an impedance matching capability into our test facility. The ability to match impedance between the transmission line and plasma load is nearly universal in microwave plasma sources, but has been absent thus far in testing at The Aerospace Corporation. Preliminary performance results incorporating impedance matching may be available.

[1] K.D. Diamant, J.E. Brandenburg, and R.B. Cohen, "High Power Microwave Electrothermal Thruster Performance on Water," AIAA Paper 2002-3662, 38th Joint Propulsion Conference, 7-10 July, 2002, Indianapolis, IN.

High Average and Peak Power Integrated Laser for Propulsion

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We describe how the unique environment of space provides an opportunity to generate high average and high peak optical power useful for propulsion. We give specific details characterizing design of a monolithic laser oscillator operating at megawatt average and terawatt peak power in near-Earth space. Direct solar illumination of the gain element provides a cost effective source of pump power. The basic gain element of the laser utilizes a novel strategy for overcoming thermal barriers that have long hindered the scaling of solid state lasers to high power. We give special attention to integration of the generation and amplification functions within the single laser oscillator. This integration is facilitated by removal of thermal barriers to power scaling, the large dimensions accessible in space based systems, and our particular choice of diamond and sapphire materials. We anticipate that the high quality optical power offered by this laser design will be useful for lift-to-orbit, optical power beaming, and to some degree, for exploration of the solar system. We provide a road map for developing such a space based laser within the next decade and applying that laser to optical power beaming and propulsion in space oriented applications.

Laser Application for the Control of Satellite Orbits

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In recent years in a number of countries (USA, Japan, Germany, France etc.) the investigations of possibilities of small-scale satellites launching into low earth orbit are being successfully conducting using high-power lasers. The cost of the satellites launching mentioned above is essentially reduced compared with traditional methods (chemical rockets). However the problem is to increase the life time of the satellites. Using lasers one can correct the spatial orientation of satellite and its equipment. In the paper the problems related to an optimal physical conditions of correction of satellite orbit parameters and the spatial orientation of its apparatus are discussed including the choice of material for ablation, laser beam intensity, type of laser facility and so on.

Investigation of Plasma Plume Dynamics by ICCD Imaging for Ablative Laser Propulsion

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This work studies the spatial and temporal dynamics of laser-induced plasma plumes (LIPP) for Ablative Laser Propulsion (ALP). A time-resolved Intensified Charged Coupled Devised (ICCD) imager (18 ns minimum time delay, 75 μm spatial resolution, 5 ns gating speed) has been utilized to investigate the expansion of the LIPP produced by focusing output pulses of a laser system (100-ps wide pulses at 532 nm wavelength and energy ~35mJ) onto a range of elementary targets. Plume expansion was studied in vacuum (~ $3x10^{-3}$ Torr). The sequence of frames of the luminous plasma plume generated near the target surface was recorded using this fast gated ICCD camera. The 3D plasma expansion velocity profiles have been derived from plasma edge intensity contours. Specific impulse (I_{sp}) was then deduced from the plasma expansion velocity profiles. Comparative analysis of these data with conducted earlier time-of-flight (TOF) measurements of the ionic component ejected from a lased-ablated target is presented.

Analysis of Two-Pulsed Ablation of Elementary Targets for Ablative Laser Propulsion

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Following on previous studies of Ablative Laser Propulsion (ALP), this ongoing work investigates the effects of temporally separated laser pulses on measured ablation parameters of elementary targets. The separation and delay of the 100 ps-duration pulses within the 0.1 – 4.0 ns range is conducted using a custom-built modification of a Michelson interferometer. The experimental proof of temporal and spatial coincidence of the pulses is presented. Ion velocity and number density are measured for each element using a time-of-flight (TOF) energy analyzer and presented as functions of relative delay between the pulses. Possible models for observed phenomena are discussed.

Solar Thermal Propulsion Improvements at Marshall Space Flight Center

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Solar Thermal Propulsion (STP) is a concept which operates by transferring solar energy to a propellant, which thermally expands through a nozzle. The specific impulse performance is about twice that of chemical combustions engines, since there is no need for an oxidizer. In orbit, an inflatable concentrator mirror captures sunlight and focuses it inside an engine absorber cavity/heat exchanger, which then heats the propellant. The primary application of STP is with upperstages taking payloads from low earth orbit to geosynchronous earth orbit or earth escape velocities.

STP engines are made of high temperature materials since heat exchanger operation requires temperatures greater than 2500K. Refractory metals such as tungsten and rhenium have been examined. The materials must also be compatible with hot hydrogen propellant. MSFC has three different engine designs, made of different refractory metal materials ready to test.

Future engines will be made of high temperature carbide materials, which can withstand temperatures greater than 3000K, hot hydrogen, and provide higher performance. A specific impulse greater than 1000 seconds greatly reduces the amount of required propellant.

A special 10kW solar ground test facility was made at MSFC to test various STP engine designs. The heliostat mirror, with dual-axis gear drive, tracks and reflects sunlight to the 18 ft. diameter concentrator mirror. The concentrator then focuses sunlight through a vacuum chamber window to a small focal point inside the STP engine. The facility closely simulates how the STP engine would function in orbit. The flux intensity at the focal point is equivalent to the intensity at a distance of 7 solar radii from the sun.

Discussions

Beamed Energy Propulsion

- Status of the Water MET at The Aerospace Corporation, Kevin D. Diamant and Ronald B. Cohen (Aerospace Corporation)
- High Average and Peak Power Integrated Laser for Propulsion, Richard L. Fork et al. (U. of Alabama in Huntsville)
- Laser Application for the Control of Satellite Orbits, Anatoliy F. Nastoyashchii (Troitsk Institute for Innovation and Fusion Research, Troitsk, Moscow Reg., Russia)
- Investigation of Plasma Plume Dynamics by ICCD Imaging for Ablative Laser Propulsion, Jun Lin et al. (U. of Alabama, Huntsville)
- Analysis of Two-Pulsed Ablation of Elementary Targets for Ablative Laser Propulsion, M. Shane Thompson et al. (Information Systems Laboratories, Inc.)
- Solar Thermal Propulsion Improvements at Marshall Space Flight Center, Harold P. Gerrish Jr. (NASA MSFC)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Propellantless Propulsion

- Characterization of Candidate Solar Sail Materials Subjected to Electron Radiation, David Edwards et al. (NASA MSFC)
- Navigating Through Space: Continuous Thrust Trajectories in 3-D, Ulyana Horodyskyj (Padua Franciscan High School)
- Solar Sail Attitude Dynamics & Control, Benjamin L. Diedrich
- A Lightweight, Low-Cost, and Simple De-Orbit System, Kerry T. Nock et al. (Global Aerospace Corporation)
- Hypersonic Waveriders and Aero-Gravity Assist Missions, James Randolph et al. (JPL)
- MSFC MXER Tether Study - Interim Report, Tara Polsgrove (NASA MSFC)
- The Space Elevator, Bradley C. Edwards (Institute for Scientific Research)
- UltraSail, R. Burton et al. (CU Aerospace)
- Discussions

Characterization of Candidate Solar Sail Materials Subjected to Electron Radiation

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The concept of using photon pressure for propulsion has been considered since Tsiolkovsky in 1921 [1-7]. In fact, Tsiolkovsky and Tsander wrote of "using tremendous mirrors of very thin sheets" and "using the pressure of sunlight to attain cosmic velocities" in 1924 [1-4]. The term "solar sailing" was coined in the late 1950s and was popularized by Arthur C. Clarke in the short story *Sunjammer* (The Wind From the Sun) in May 1964 [5]. The National Aeronautics and Space Administration (NASA) used sailing techniques to extend the operational life of the Mariner 10 spacecraft in 1974-1975. A problem in the control system was causing Mariner 10 to go off course. By controlling the attitude of Mariner 10 and the angle of the solar power panels relative to the Sun, ground controllers were able to correct the problem without using precious fuel [4, 6, 7].

Solar sailing is a unique form of propulsion where a spacecraft gains momentum from incident photons. Solar sails are not limited by reaction mass and provide continual acceleration, reduced only by the lifetime of the lightweight film in the space environment and the distance to the Sun. Once thought to be difficult or impossible, solar sailing has come out of science fiction and into the realm of possibility. Any spacecraft using this method would need to deploy a thin sail that could be as large as many kilometers in extent. The availability of strong, ultra lightweight, and radiation resistant materials will determine the future of solar sailing.

The National Aeronautics and Space Administration's Marshall Space Flight Center (MSFC) is concentrating research into the utilization of ultra lightweight materials for spacecraft propulsion. The Space Environmental Effects Team at MSFC is actively characterizing candidate solar sail material to evaluate the thermo-optical and mechanical properties after exposure to electron radiation. Practical sails must be resistant to the effects of long duration electron exposure. For this reason, research was initiated using a 50 keV electron source to determine the hardness of several candidate sail materials. Hardness in this context is defined as the amount of electron fluence (electrons/area) required to cause the sail material to fail. Solar sails are generally composed of a highly reflective metallic front layer, a thin polymeric substrate, and occasionally a highly emissive back surface. State-of-the-art candidate solar sail materials are generally composed of a polymeric substrate that is 2 to 3 microns thick. This polymeric film is coated with a thin metallic layer, usually aluminum. A typical thickness for this metallic layer is 50 nm. Candidate solar sail materials, aluminized Mylar™ [8], aluminized Uplex and aluminized Kapton™ [8] are being characterized under this test plan. A radiation dose versus material depth profile was generated for each candidate sail material. This dose-depth profile was used to determine the relationship between the 50 keV electron fluence and radiation dose in the sail material. The focus of this investigation was to determine the effect of a uniform dose of 50 keV electron radiation on the sail material mechanical properties. Candidate sail materials were loaded, in tension, and exposed to electron radiation. The radiation dose levels, at material failure, were recorded and will be shown as a function of engineering stress. This paper will discuss the preliminary results of this research.

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Keywords: solar sail, electron exposure, and space radiation environment.

Navigating Through Space: Continuous Thrust Trajectories in 3-D

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This research examined properties of a solar sail, a method of space propulsion that needs no fuel. Instead, it uses sunlight and gravity to generate continuous thrust. The relationship between thrust, mass-to-area (M/A) ratio, and the solar sail's orientation relative to the sun as determined by its "cone" and "clock" angles was investigated. The hypothesis was that a solar sail's maximum displacement in the z direction (out-of-plane) occurs at the same combination of cone and clock angles independent of the M/A ratio.

A computer simulation using MATLAB was developed to model interplanetary solar sail trajectories in 3-D taking into account the differing orbital inclinations of the planets as they travel around the sun. Solutions to selected missions previously designed in 2-D were re-evaluated using an improved genetic algorithm incorporating concepts from geometric algebra and differential equations. An unusual figure was discovered that related thrust magnitude and orientation to cone and clock angles. A parametric equation for the curve was developed. Further, maximum z displacement was found to vary with M/A ratio, as well as with sail orientation.

Solar Sail Attitude Dynamics & Control

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An analysis of the attitude dynamics and control of a solar sail is presented. The dynamics are developed for an imperfect solar sail with a gimbaled boom in three dimensions. System equilibrium conditions are identified, about which the dynamics are linearized. Controllability and other aspects of the linear system are examined. A linear control law is developed for the controllable rigid body states. The open loop and closed loop properties and closed loop performance are examined with the full non-linear dynamics model.

A Lightweight, Low-Cost, and Simple De-Orbit System

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Global Aerospace Corporation is developing a revolutionary concept for lowering the orbits of space objects, without propellant, that requires extremely little mass, power, and cost. Key elements of this innovative new concept are:

- Ultra lightweight, thin, large area inflatable envelope to reduce satellite ballistic coefficient by two orders of magnitude
- Operate in meteoroid, orbital debris, atomic oxygen and UV space environments
- Controlled spatial deployment of envelope
- Inflation control and pressure maintenance system

This system concept, called a Gossamer Orbit Lowering Device (GOLD), can be employed at any planet that has an atmosphere. Essentially, the system increases the cross-section area of a satellite in order to increase atmospheric drag, or momentum exchange with atmospheric molecules, that over time results in a lowering of satellite velocity and subsequent orbit lowering. For example, if the cross-section area of an Earth satellite can be increased by about 100 times, the satellite can be de-orbited in one week instead of a natural de-orbit time of two years. Key features of the GOLD system concept include:

- accelerates natural orbit lowering,
- does not contribute to orbit debris problem,
- operates autonomously and with very little power,
- made of very lightweight materials,
- can be designed and integrated into space vehicles planned for launch into space,
- can function after a satellite has failed,
- capable of being installed on derelict space objects already in orbit,
- adapts to increasing atmospheric pressure as the orbit altitude is lowered and,
- functions in meteoroid, orbital debris, atomic oxygen and UV space environments.

The GOLD system is a unique combination of space inflatable, aerobraking, terrestrial balloon, thin film structure, and material technologies. Space inflatable technology is not new, however the application to orbit change, the two order of magnitude decrease in ballistic coefficient, the specific combination of ultra lightweight envelopes, innovative deployment, and inflation control and maintenance technologies are new and unique. The GOLD concept will be described, its advantages and performance detailed, and its applications discussed.

Hypersonic Waveriders and Aero-Gravity Assist Missions

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JPL

Todd Mosher
USU

The development of a hypersonic waverider for interplanetary travel promises to revolutionize deep space transportation to bodies with atmospheres. The waverider would enable the Aero-Gravity Assist (AGA) maneuvers at the intermediate planets and aerocapture orbit insertion at the terminal body with an atmosphere. The mission and system requirements as well as the design concept for the waverider will be presented. In addition, the unique trajectory characteristics will emphasize the short flight durations with the immense ΔVs possible at each encounter with a terrestrial planet. Example missions will be presented.

MSFC MXER Tether Study - Interim Report

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Momentum exchange / electrodynamic reboost (MXER) tether systems offer the potential for nearly propellantless delta V transfer to multiple payloads. Engineers at Marshall Space Flight Center are studying the use of this system to transfer payloads from low earth orbit to geostationary transfer orbit. The current preliminary concept for the tether system will be presented as well as an interim design of a Payload Accommodation Assembly (PAA). The PAA includes everything required to perform the rendezvous with the tether: GN&C components, delta V capability (both for rendezvous and GEO circularization), and a grapple hook that will snare a passive catch mechanism on the tether tip.

The Space Elevator

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The space elevator first appeared in 1960 (Artsutanov) in a Russian technical journal. In the following years the concept appeared several times in technical journals (Isaacs, 1966; Pearson, 1975; Arthur C. Clarke, 1979) and then began to appear in science fiction (Arthur C. Clarke, 1978; Stanley Robinson, 1993). More recently, 1999, NASA held a meeting to examine the possible design of a space elevator (Smitherman, 2000) The simplest explanation of the space elevator concept is that it is a ribbon with one end attached to the Earth's surface and the other end in space beyond geosynchronous orbit (35,800 km altitude). The competing forces of gravity at the lower end and outward centripetal acceleration at the farther end keep the cable under tension and stationary over a single position on Earth. This ribbon can be gently ascended or descended by mechanical means to or from Earth orbit or used as a sling to deliver payloads to neighboring planets.

Funded by a NASA grant, our program has defined a complete space elevator that can be constructed, deployed and operated using current or near-term technology. In our scenario an initial ribbon (8 inches wide and thinner than paper) is deployed using four expendable launch vehicles and conventional satellite technology. The initial ribbon with one end attached to an anchor platform and the other 62,000 miles up in space will be enlarged using mechanical climbers. Each climber will ascend the ribbon and add to it until a complete elevator is achieved. The final system will have a ribbon that is three feet wide and thinner than paper, an ocean-going anchor platform located in the eastern equatorial Pacific, a laser power beaming system, a debris tracking system and mechanical climbers capable of delivering 13 ton payloads to any Earth orbit or the neighboring planets. The total capacity of the system will be roughly 1000 tons per year at an operating cost of $100/lb to any Earth orbit, or location between Venus and the outer asteroid belt. The complete system has been designed with solutions for all of the major challenges. The estimated construction cost is $10B and can be operational in 15 years.

The ribbon, being the only component of the space elevator not available or under design for another program, is the last hurdle prior to construction of the space elevator. The sheer length, 62,000 miles, is considerable but is well within current technology. The material required for construction of the cable is a carbon nanotube composite: currently under development and will be available in 2 years.

The space elevator would allow for the launch of large fragile structures such as solar power satellites to provide clean renewable energy to Earth, unsurpassed Earth observation possibilities for intelligence and military applications, commercial manufacturing facilities, inexpensive stations for manned activities, and payloads for exploration and development of space.

Current strategy calls for $40M in development funds over the next two years with construction beginning immediately following this design stage.

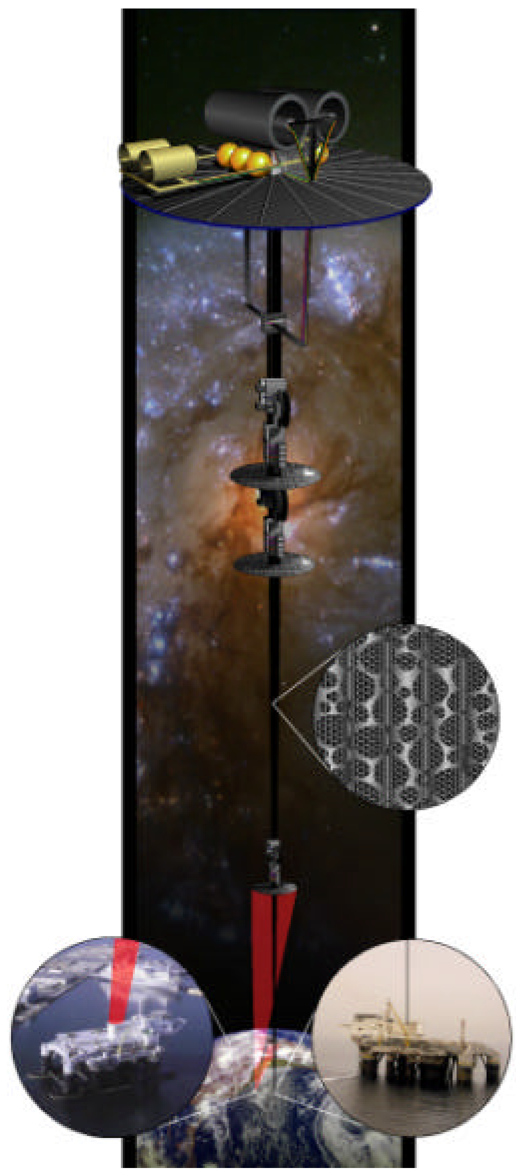

Figure 1. Artist conception of the proposed space elevator.

UltraSail

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UltraSail is a complete sail system for the launch, deployment, stabilization and control of very large solar sails enabling reduced mission times for interplanetary and deep space spacecraft. UltraSail is an innovative, non-traditional approach to propulsion technology achieved by combining propulsion and control systems developed for formation-flying microsatellites with an innovative solar sail architecture to achieve km^2-class controllable sail areas, sail subsystem area densities of 1 gm/m^2, and thrust levels equivalent to 400 kW ion thruster systems used for comparable deep space missions. UltraSail can conceivably even achieve outer planetary rendezvous, a deep space capability now reserved for high-mass nuclear and chemical systems. Ultrasail is a Delta IV-launched multi-blade spin-stabilized system with blade lengths as long as 50 km, reminiscent of the MacNeal Heliogyro. The primary innovation is the near-elimination of sail supporting structures by attaching the sail tip to a rigid formation-flying microsatellite truss which deploys the sail blade, and which then articulates the blade to provide attitude control, including spin stabilization and precession of the spin axis. These tip microsatellites are controlled by a solar-powered 3-axis microthruster system (electric or cold gas) to maintain proper sail film tension during deployment and spin-up. The satellite mass also provides a stabilizing centrifugal force on the blade while in rotation.

Understanding the dynamics of individual blades is key to the overall dynamics of UltraSail. Forces and torques that must be modeled include those due to solar pressure, those generated by the microsatellite at the blade tip and by torques applied at the blade root. Centrifugal forces also play a significant role in the deployment and maintenance of the sail configuration. To capture the dynamics of the overall system, the equations of motion for the blades have been derived. Using these differential equations, a control law will be derived to maneuver UltraSail. This law involves the pitching of the individual blades thereby moving the distribution of the radiation pressure on each individual blade and inducing a resultant torque on the system. The direction of the angular momentum vector and its rate of precession can be controlled through the pitch angle of the blades.

The UltraSail trajectory is also being studied. Optimal or near-optimal trajectories are being generated to showcase UltraSail performance. Various missions, e.g. outer planet and solar polar missions for observation of the Sun, are currently being investigated to demonstrate the performance enhancements generated by UltraSail technology. Calculus-of-variations-based optimization software is used to produce optimal UltraSail trajectories. The performance of these trajectories is being compared to optimal results generated with other propulsion models, including chemical propulsion, ion propulsion, and competing solar sail concepts. Results of these studies will quantify the performance of UltraSail compared to existing solar sail concepts for high energy missions.

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Discussions

Propellantless Propulsion

- Characterization of Candidate Solar Sail Materials Subjected to Electron Radiation, David Edwards et al. (NASA MSFC)
- Navigating Through Space: Continuous Thrust Trajectories in 3-D, Ulyana Horodyskyj (Padua Franciscan High School)
- Solar Sail Attitude Dynamics & Control, Benjamin L. Diedrich
- A Lightweight, Low-Cost, and Simple De-Orbit System, Kerry T. Nock et al. (Global Aerospace Corporation)
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- The Space Elevator, Bradley C. Edwards (Institute for Scientific Research)
- UltraSail, R. Burton et al. (CU Aerospace)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Nuclear Propulsion

FISSION

- Nuclear Isomers, Hill Roberts (SRS Technologies)
- Min-MagOrion: A Pulsed Nuclear Rocket for Crewed Solar System Exploration, Ralph Ewig and Dana Andrews (Andrews Space & Technology)
- Pulsed Magnetic Field Driven Gas Core Reactors for Space Power & Propulsion Applications, Samim Anghaie (U. of Florida) and Carey Butler (Institute for Scientific Research)
- Discussions

FUSION

- Propulsion Using an Improved Colliding Toroid Fusion Reactor, Clint Seward (Electron Power Systems, Inc.)
- Colliding Beam Fusion Reactor Space Propulsion System, A. Cheung et al. (U. of California, Irvine)
- Experimental Simulation of a Proton Collimator for a Fusion Space Thruster, G. H. Miley et al. (U. of Illinois)
- Mini-Fusion-Fission Explosive Devices for Nuclear Pulse Propulsion, F. Winterberg (U. of Nevada, Reno)
- MetaStable Deuterium (MSD) as Cold Fusion Fuel, Robert W. Bass et al. (BAE SYSTEMS North America)
- Discussions

ANTIMATTER

- Review of the High Performance Antiproton Trap (HiPAT) Experiment at the Marshall Space Flight Center, Herb Sims (NASA MSFC)
- Antimatter Driven Sail for Deep Space Missions, Steven D. Howe and Gerald P. Jackson (Hbar Technologies, LLC)
- Discussions

Nuclear Isomers

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The potential uses of nuclear isomers in space power and space propulsion is reviewed, with emphasis on triggered isotropic energy release from long-lived mid-mass isomers such as Hf-178m2 (31 year half-life). Triggering characterization studies using synchrotron radiation as the probe are presented. Potential isomer production technologies are reviewed. Propulsion concepts under evaluation include thermal conversion and nuclear gamma ray laser photon momentum propulsion concepts.

Min-MagOrion: A Pulsed Nuclear Rocket for Crewed Solar System Exploration

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Andrews Space & Technology has recently concluded a NASA SBIR for the investigation and experimental verification of the Mini-MagOrion (MMO) concept. The MMO concept is a GigaJoule scale pulsed nuclear fission device, where low mass criticality is accomplished by the electromagnetic compression of individual fission pellets. The resulting fission reaction produces a highly energetic plasma, which is then expanded through a magnetic nozzle. Experiments on the Sandia National Laboratory Saturn and Z pulsed power machines were utilized to determine concept feasibility, and the results are presented. The design of the propulsion system based on the Mini-MagOrion concept, together with a look at the accompanying vehicle design and anticipated system performance are also discussed. An analysis of engine / nozzle interaction is presented, together with associated requirements on the vehicles power and thermal management subsystems. Vehicle performance assessments are given for crewed and robotic missions to the inner and outer solar system, indicating favorable capabilities based on near-term achievable technology.

Pulsed Magnetic Field Driven Gas Core Reactors for Space Power & Propulsion Applications

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A pulsed Gas Core Reactor (P-GCR) concept based on using non-moving fissile gas is designed. The concept utilizes well-established fusion plasma confinement and compression method to achieve supercritical condition in a highly subcritical configuration. In particular, electromagnetic induced shock wave compaction and gas dynamic trap techniques are merged to bring a relatively small volume (~ 1 m^3) of fissile (^{235}U, ^{233}U, ^{239}Pu, or ^{242m}Am) gas compounds to supercritical condition, thereby, releasing an intense pulse of fission power. A magnetic field compaction scheme is designed to directly convert the fission energy to electricity. The estimated specific power of the pulsed magnetic field driven Nuclear Electric Propulsion (NEP) system is above 1 KWe/Kg.

An alternative P-GCR design option provides direct thrust in nuclear thermal propulsion configuration. The direct propulsion system is designed based on a merger between Magnetized Target Fusion (MTF) and hydrodynamic confinement techniques to achieve long duration (~ 100 to 1000 ms) criticality and ultrahigh burnup in a fissile gas. The MTF technique induces large pressure ratio (~ 10) adiabatic compaction of fissile gas by rapid collapsing of a cylindrical layer of a low neutron absorbing metal (Al or Zr). Hydrodynamic confinement in a leaky reversed mirror configuration is used to contain and direct the fission plasma through a nozzle, thereby, generating intense thrust (~ 100's of Klb) at specific impulse levels in excess of 2000 seconds.

Discussions

Fission Thermal Propulsion

- Nuclear Isomers, Hill Roberts (SRS Technologies)
- Min-MagOrion: A Pulsed Nuclear Rocket for Crewed Solar System Exploration, Ralph Ewig and Dana Andrews (Andrews Space & Technology)
- Pulsed Magnetic Field Driven Gas Core Reactors for Space Power & Propulsion Applications, Samim Anghaie (U. of Florida) and Carey Butler (Institute for Scientific Research)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Propulsion Using an Improved Colliding Toroid Fusion Reactor

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The TRISOPS project succeeded in producing fusion in the late 1970's by colliding two plasma toroids. TRISOPS could only produce small amounts of energy due to plasma toroid limitations, and so the project was almost forgotten. Newly discovered electron spiral toroid (EST) technology will potentially overcome the TRISOPS limitations to produce a practical, small colliding toroid fusion reactor (CFTR).

TRISOPS plasma toroids had limited reaction times because they dissipated in tens of microseconds. TRISOPS ion energy was limited to well below optimum fusion energies. TRISOPS ion density limit was too low.

Patented stable plasma toroids, called electron spiral toroids (EST's), remain stable in partial atmosphere with no magnetic fields for containment and will potentially overcome each TRISOPS limitation. EST's are observed for hundreds of milliseconds, potentially increasing TRISOPS fusion reaction time from tens of microseconds to hundreds of milliseconds. EST's are accelerated magnetically to add energy, potentially reaching optimum fusion energies using directed kinetic energy instead of thermal energy. Calculations show that the EST ions are much denser than the TRISOPS ions. With these improvements a CTFR will potentially exceed break even.

A small fusion reactor will have significant benefits for space propulsion and power generation. Without overstating the obvious potential, design calculations show that a fusion reactor will replace 30,000 pounds of jet fuel with 2.2 pounds of fusion fuel in systems that are similar in size and mass to today's propulsion systems and power systems.

As an example, Earth to Orbit launch vehicles could potentially use fusion energy in place of fuel combustion, thus reducing launch vehicle mass at liftoff by about 90%. First, a jet/ramjet engine would heat air for thrust using fusion energy instead of combustion, reducing by 10,000 times the fuel load mass to fly from 0 km to 100 km. Secondly, the potential is that air is used for lift-off propellant instead of on-board propellant. Launch vehicle velocity could achieve orbit velocity at 100km using NASA Hyper-X technology, which achieved manageable skin temperatures at 30.5 km and 3212-m/s. Increasing to orbit velocity of 7671-m/s at 100 km should be achievable.

As another example, a D-T fusion reactor in space would use hydrogen for fuel as well as for propellant. Hydrogen can be collected in space from many locations, and thus an interstellar mission might be able to minimize fuel mass and propellant mass carried on-board.

Technology readiness level is 3. TRISOPS produced fusion. EST's are produced in the lab, and MIT scientists confirmed the EST physics on a recent STTR project. EST's are accelerated using magnetic pressure. Design calculations are completed for the CTFR. What remains to be done is to build a CTFR in the lab. A project will reach TRL 4 within three years.

Colliding Beam Fusion Reactor Space Propulsion System

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The Colliding Beam Fusion Reactor Space Propulsion System (CBFR SPS) is an energetic-ion, magnetic-field reversed configuration. The reactor is fueled by a 50:50 mix of hydrogen-boron(11). Helium ions are expelled out of the fusion core along the system's axis of symmetry. Ions flowing in one direction are decelerated and their energy recovered to "power" the system. Ions expelled in the other direction provide thrust.

The plasma equilibrium is described by the Vlasov-Maxwell equation and a Fokker Planck collision operator; all sources and sinks for energy and particle flow are included. The azimuthal velocities and temperatures of the fuel ions are equal and the FRC plasma current is un-neutralized by electrons. The dimensions of the confinement system are comparable to the ion gyro-radius. Classical transport and energy confinement is predicted, and the device is scaleable.

We are developing a systems model for the CBFR SPS that accounts for realistic design parameters of the component hardware and predictable performance; the objective is to provide a means to evaluate system tradeoffs leading to an optimized design. To date we have obtained estimates for the propulsion parameters and subsystem masses, including thermal control, for a 100 MW propulsion module.

Experimental Simulation of a Proton Collimator for a Fusion Space Thruster

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The advantages of using a D^3He fusion reactor using an IEC type fusion devise for a deep space mission was demonstrated in a recent paper titled "Fusion Ship II", presented at the STAIF 2003 meeting [1]. One of the fundamental issues in this approach is how to extract and collimate the 14-MeV protons (fusion products) generated isotropically in the D-^3He fusion reactor. In the Space Ship II design, this was done using a special magnetic field collimator. NPL Associates and the University of Illinois are currently developing an experiment to simulate and study this collimator. A low-energy electron source is used to simulate the protons, and all components are scaled accordingly. This collimator unit has just become operational, and its design and initial operation, will be described.

The SIEC region must be free of magnetic field in order to focus the fusion fuel ion beam to the spherical center. Thus, a pair of Helmholtz coils are located anti-parallel to the magnetic collimator channel. The IEC fusion source (or electron source in present experiments) is then located at the center of these coils. Protons are guided by the magnetic channel to traveling wave direct energy converter or to direct proton thrusters. In addition to forming a proton beam, the collimator makes it possible to couple multiple IEC fusion devices in series, increasing the overall fusion power and improving the energy confinement of a fusion system.

[1] R. Burton, H. Momota, N. Richardson, Y. Shaban, and G. H. Miley, "Fusion Ship II- A Fast Manned Interplanetary Space Vehicle Using Inertial Electrostatic Fusion," *Space Technology and Applications Forum (STAIF-2003)*, AIP Conference Proceedings, (2003).

Mini-Fusion-Fission Explosive Devices for Nuclear Pulse Propulsion

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Nuclear pulse propulsion demands low yield nuclear explosive devices. Because the critical mass of a fission explosive is rather large, this leads to extravagant fission devices with a very low fuel burn up. For non-fission ignited pure fusion microexplosions the problem is the large ignition apparatus (laser, particle beam etc.). Fission ignited large fusion explosive devices are for obvious reasons even less desirable. A third category (mini-nukes) are devices where the critical mass of the fission explosive is substantially reduced by its coupling to a DT fusion reaction, with the DT fusion neutrons increasing the fission rate. Whereas in pure fission devices a reduction of the critical mass is achieved by the implosive compression of the fissle core with a chemical high explosive, in the third category the implosion must at the same time heat the DT surrounding the fissle core to a temperature of = 10^7 °K, at which enough fusion neutrons are generated to increase the fission rate which in turn further increases the temperature and fusion neutron production rate. As it had been shown by the author many years ago, such mini-nukes lead to astonishingly small critical masses.

In their application to nuclear pulse propulsion the combustion products from the chemical high explosive are further heated by the neutrons and are becoming part of the propellant.

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Winterberg, F., Micro-Fission Explosions and Controlled Release of Thermonuclear Energy. Nature 241 449 (1973).

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Winterberg, F., Laser Produced Plasmas with Fissionable Material, Presented at Third International Workshop on "Laser Interaction and Related Plasma Phenomena", held at Rensselaer Polytechnic Institute, Troy, New York, August 13-17, 1973. Plenum Publishing Corporation, New York.

MetaStable Deuterium (MSD) as Cold Fusion Fuel

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The reality of the phenomenon of Cold Fusion, defined to be the Low Energy Nuclear Reaction (LENR)

$$\text{(ANEUTRONIC)} \quad d + d \rightarrow {}^4He + 24\ \text{MeV (lattice phonons)},$$

is now far more credible than it was at ASPW2001. This view is particularly true in light of the papers presented at ICCF9 in Tsinghua University, Peking, China, on 20-24 May, 2002:

http://iccf9.global.tsinghua.edu.cn/E-%20default.htm

and at a Cold Fusion session of the American Physical Society in Austin, TX, on 3/7/03:

http://www.aps.org/meet/MAR03/baps/abs/S9530.html .

At the APS conference, 10 respected scientists, most of whom have worked in this field for the past 13 years, presented their latest positive results. More personally, a major funding source is negotiating with a major university laboratory about the possibility of performing my "layman-conviction oriented" *Five Frozen Needles Cold Fusion Protocol* experiment,

http://www.lenr-canr.org/acrobat/BassRWfivefrozen.pdf

previously published both in *Infinite Energy* magazine/journal and in the *Journal of New Energy*, with the intention of attaining results to be announced at the 24-29 August 2003 ICCF10 in Cambridge (with hoped-for discomfiture of the established skeptics at nearby Harvard & MIT). This protocol is designed to be conclusively definitive to experts and intuitively convincing to laymen regarding the reality of CF/LENR.

My ASPW2001 presentation described conceptually new ways of storing, transmitting, and generating energy, which can be realized through the production of metamatter. In order to achieve this goal, two questions must be answered positively. First, is it technically feasible to convert a gas into a pressure-ionized plasma in the state of a liquid metal that is self-cohesively self-confined yet fully ionized – a liquid metallic plasmoid (LMP)? Second, can an LMP be crystallized as it cools? The resulting crystal, if producible, is metamatter. Depending on the gas used -- helium, hydrogen, heavy hydrogen – this process will produce, respectively, crystals of metastable helium (MSH), metastable protium (MSP) or metastable deuterium (MSD). These crystals offer potentially revolutionary ways of addressing energy needs. One cm^3 of MSD can be fused via the above-cited LENR to an "ash" of harmless, inert, useful helium together with the heat-energy equivalent of 15 tons of high-energy explosive or conventional chemical rocket-propellant. What are the design parameters of a *Proof-of-Principle Producibility Protocol* for demonstration of the feasibility of production of the MSD precursor LMP? The new presentation addresses this query quantitatively from first principles.

Discussions

Fusion Propulsion

- Propulsion Using an Improved Colliding Toroid Fusion Reactor, Clint Seward (Electron Power Systems, Inc.)
- Colliding Beam Fusion Reactor Space Propulsion System, A. Cheung et al. (U. of California, Irvine)
- Experimental Simulation of a Proton Collimator for a Fusion Space Thruster, G. H. Miley et al. (U. of Illinois)
- Mini-Fusion-Fission Explosive Devices for Nuclear Pulse Propulsion, F. Winterberg (U. of Nevada, Reno)
- MetaStable Deuterium (MSD) as Cold Fusion Fuel, Robert W. Bass et al. (BAE SYSTEMS North America)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Review of the High Performance Antiproton Trap (HiPAT) Experiment at the Marshall Space Flight Center

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The significant energy density of matter-antimatter annihilation is attractive to the designers of future space propulsion systems, with the potential to offer a highly compact source of power. Many propulsion concepts exist that could take advantage of matter-antimatter reactions, and current antiproton production rates are sufficient to support basic proof-of-principle evaluation of technology associated with antimatter-derived propulsion. One enabling technology for such experiments is portable storage of low energy antiprotons, allowing antiprotons to be trapped, stored, and transported for use at an experimental facility.

To address this need, the Marshall Space Flight Center's Propulsion Research Center is developing a storage system referred to as the High Performance Antiproton Trap (HiPAT) with a design goal of containing 10^{12} particles for up to 18 days. The HiPAT makes use of an electromagnetic system (Penning-Malmberg design) consisting of a 4 Telsa superconductor, high voltage electrode structure, Radio Frequency (RF) network, and ultra high vacuum system. To evaluate the system "normal matter" sources (both electron guns and ion sources) are used to generate charge particles. The electron beams ionize gas within the trapping region producing ions insitu, whereas the ion sources produce the particles external to the trapping region and required dynamic capture. A wide range of experiments has been performed examining factors such as ion storage lifetimes, effect of RF energy on storage lifetime, and ability to routinely perform dynamic ion capture.

Current effort has been focused on improving the RF rotating wall system to permit longer storage times and non-destructive diagnostics of stored ions. Typical particle detection is performed by extracting trapped ions from HiPAT and destructively colliding them with a micro-channel plate detector (providing number and energy information). This improved RF system has been used to detect various plasma modes for both electron and ion plasmas in the two traps at MSFC, including axial, cyclotron, and diocotron modes. New diagnostics are also being added to HiPAT to measure the axial density distribution of the trapped cloud to match measured RF plasma modes to plasma conditions.

Antimatter Driven Sail for Deep Space Missions

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Recent discoveries in observational astronomy made during the past decade have revolutionized our understanding of the universe, our galaxy, and our solar system's local environment. The existence of a ring of asteroids around our solar system, of large unseen clouds of dust in the interstellar neighborhood, and of the potential presence of "dark matter" throughout the universe have all drastically altered our view of cosmology. However, direct observation of some of these major concepts has yet to be accomplished.

We have evaluated the concept of the Antimatter Driven Sail (ADS). The mission we evaluated was sending a probe to 250 AU, the Kuiper Belt, in 10 years. Such a mission is still beyond the capability of NASA or any other agency using currently available technology. We examined three major areas: Mission Architecture, Subsystem Technologies, and a Technology Roadmap. The Mission Architecture effort has focused on developing an integrated systems model to evaluate the performance of the entire spacecraft for a mission. The Subsystem Technologies investigation examined 1) the fundamental reactions between the antiprotons and the sail material and the subsequent momentum transfer, 2) a concept for storing antihydrogen at high densities, and 3) an entirely new concept for electrical power production. The new electrical-power concept may have applicability to nearer-term space missions as a power supply if the availability of antiprotons becomes common. In developing the Technology Roadmap, we examined the potential 1) for using recent developments in antiproton storage and antihydrogen formation to create a path to ultra-high density antihydrogen storage, and 2) for increasing production of antiprotons by modifying the existing Fermilab facility.

Our system analysis indicates that the ADS system would enable a 10 kg instrument payload could be sent to 250 AU in 10 years using 30 milligrams of antihydrogen. This amount of antimatter is clearly within the production potential of the US within the next 40 years using currently accepted accelerator technologies. In addition, preliminary calculations also indicate that this architecture could enable a similar probe to be sent to the next star, Alpha Centauri, in 40 years using gram-scale quantities of antimatter. The antimatter driven sail may in-fact allow humanity to consider sending probes to the stars.

Discussions

Antimatter Propulsion

- Review of the High Performance Antiproton Trap (HiPAT) Experiment at the Marshall Space Flight Center, Herb Sims (NASA MSFC)
- Antimatter Driven Sail for Deep Space Missions, Steven D. Howe and Gerald P. Jackson (Hbar Technologies, LLC)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Advanced Electric Propulsion

POWER SYSTEMS

- NEMO: Exploration of Europa's Sub-Surface Ocean and Return of Samples to Earth Using Nuclear Propulsion, John Paniagua et al. (Plus Ultra Technologies)
- Nuclear Electric Systems Analyses and Technology Development Options for Outer Planet Missions, Benjamin Donahue (Boeing Phantom Works)
- SUSEE: An Ultra Lightweight Nuclear Electric Propulsion System Based on Existing Water Reactor and Steam Cycle Technology, James Powell et al. (Plus Ultra Technologies)
- Recent Developments in Vapor Core Reactors with MHD Power Conversion for Space Power Systems, Travis Knight and Samim Anghaie (U. of Florida)
- Discussions

THRUSTERS

- Technologies to Improve Ion Engine Performance, Life and Efficiency for NEP, Ira Katz et al. (NASA JPL)
- Sputter Yield and Erosion Measurements For Ion Thruster Materials, Azer Yalin, John Williams, and Paul Wilbur (Colorado State U.)
- High Power MPD Thruster Research at the NASA Glenn Research Center, Michael R. LaPointe and James Gilland (Ohio Aerospace Institute)
- Wave Generated Plasma Sources for Electric Propulsion, Jim Gilland (Ohio Aerospace Institute)
- Liquid-Metal-Fed Pulsed Plasma Thrusters, T.E. Markusic (NASA MSFC)
- Recent Advances in the Development of the VASIMR Engine, Franklin R. Chang-Díaz et al. (NASA JSC)
- An Experimental Investigation of Plasma Detachment from Magnetized Thruster Plumes, M. E. Light and P. L. Colestock (LANL)
- The Plasmoid Thruster Experiment (PTX), Richard Eskridge et al. (NASA MSFC)
- Thrust Enhancement in the LAPPS Propulsion System, Terry Kammash (U. of Michigan)
- Discussions

NEMO: Exploration of Europa's sub-Surface Ocean and Return of Samples to Earth Using Nuclear Propulsion

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Europa appears to have an extensive sub-surface ocean beneath a thick (kilometers) ice sheet that covers the entire moon. Living and/or fossil life forms may be present on Europa. These could be found near hydrothermal vents or widely distributed throughout the ocean, or present as fossils trapped in tidal cracks inside the ice sheet. The proposed NEMO (Nuclear Europa Mobile Ocean) mission would explore Europa's sub-surface ocean and the interior of its ice sheet at multiple sites on Europa looking for evidence of life forms, and if found returning them to Earth along with geological samples. To perform such a mission, the NEMO spacecraft will require high thrust capability, both for landing on Europa and taking off for Earth, and for making hops to multiple separated sites on Europa. Moreover, the NEMO spacecraft will have to manufacture and replenish its propellant from Europa's ice sheet. It will also have to melt a channel down through the kilometers thick ice sheet to the sub-surface ocean, and once there, send out a submersible to explore, transmit back data, and return samples from a large area surrounding the entry point. The NEMO mission appears achievable using a compact, lightweight, bi-modal Nuclear Thermal Propulsion (NTP) engine that provides both high thrust capability and electric power for electrolyzing melt water from the ice sheet to produce liquid H_2 propellant. The NEMO spacecraft also carries a melt probe and a submersible, each powered by a very small, ultra lightweight water-cooled reactor. These reactors utilize cermet fuel similar to that used for many years in existing reactors. The design, architecture and technology of the NEMO mission are described in detail. Total mission duration is 6 years, measured from Earth departure to Earth landing of samples – 2 years to reach Europa, 1 year to explore and hop to multiple sites on Europa, and 3 years to return to Earth. There is a strong existing technology base for NEMO, so that a mission start date in the 2010 to 2012 period appears possible given a vigorous development program.

Nuclear Electric Systems Analyses and Technology Development Options for Outer Planet Missions

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Nuclear Electric Propulsion (NEP) uranium-fuel nuclear fission reactors with advanced power generation, power processing and electric propulsion systems would enable scientifically rich robotic exploration missions. Benefits would include:

- Faster trips
- Visits to multiple destinations
- Provision for high power for science at destinations
- Maintain Position and operations over long durations
- Reductions in launch window constraints
- Provisions for high power, high-rate broadband communications to Earth
- Reductions is spacecraft weight
- Reach more distant objects with orbiters
- Two way sample return missions

The objective of the paper will be to identify and present sound technical options for the formulation and implementation of exciting solar system exploration missions. Missions investigated include Titan and Neptune destinations for a variety of trip times and science payload allotments.

The work to be presented has been done under the NASA Marshall Space Flight Center, Boeing and SAIC *In-Space Technology Assessment* (ISTA) Contract. Mr. Donahue is a senior member of the Boeing Phantom Works Advanced Programs Division and has been active in evaluating advanced propulsion systems for space transfer for the last 15 years with Boeing.

The ISTA program analyses presented in this paper include established strategies for creating system wide optimizations and trade studies which are intended to facilitate good propulsion technology investments for the Nuclear System Initiative (NSI), and to provide opportunities for embedding advanced elements into flight programs when sufficiently matured. These assessments are intended to provide insight into return on investment analysis, and aid in setting forth technology roadmaps and maturation activities to enable exploration mission with 10 fold science return as compared to present chemical propulsion exploration vehicles.

Low thrust trajectory analysis is done with the VARITOP trajectory tool. Mission analyses include NEP vehicle departures from Earth escape conditions (Heliocentric velocity (C3) equal to zero), as well as departures from Nuclear Start Orbit (NSO) presently defined as 2500 nmi circular. The Boeing/ISTA NEPS Vehicle Synthesis tool models major elements of the system. Detailed technology characterizations are incorporated into the model, including a variety of advanced nuclear reactor/power generation options and configurations to enable sensitivity analyses. Mission analysis is done consistent with known and estimated technology limitations and growth allowances, such as required power system Alpha as a function of power level and trip time. Science payload vs power level and trip time, of significant interest to understanding the capabilities of NEP systems, is presented, as is the implications of the utilization of various Ion thruster combinations. High scientific return electric propulsion systems/missions must have long-lived and reliable subsystems; likewise NEPS planning must be consistent with concerns associated with nuclear systems in an Earth-to-orbit launch vehicle.

SUSEE: An Ultra Lightweight Nuclear Electric Propulsion System Based on Existing Water Reactor and Steam Cycle Technology

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SUSEE (Space NUclear Steam Electric Energy) is a compact ultra lightweight nuclear electric space power system based on existing water reactor and steam cycle technology. A specific mass of ~3 kg/KW(e) is projected for the SUSEE system (reactor, controls, turbo-generator, radiator), a factor of 10 lower than other nuclear electric space systems. Depending on design, the SUSEE system can deliver power levels ranging from ~10 KW(e) to multi-megawatts. SUSEE steam operating conditions are standard, i.e., 1000 psi (68 atm) and 1000 F (810 K). The only difference from conventional cycles is a higher condenser pressure, i.e., 2 to 3 atm at a higher condenser temperature, i.e., ~400 K, which enables efficient radiant rejection of waste heat. While higher condenser pressure reduces thermal to electric efficiency, it still is excellent for a space power system, being 23% for a single stage expansion and 32% for multi-stage expansion, based on a conservative turbine efficiency of 80%. The key SUSEE innovation is a lightweight, condensing radiator that operates in zero g. Steam condenses in multiple small parallel channels, e.g., 10 to 20 mils in diameter, that are inside thin flat metal (Al or Be) strips connecting the inlet steam header to the outlet condensate header. Surface tension forces dominate in small channels causing the condensed water to form a series of slugs that travel towards the outlet header. The specific area of the SUSEE radiator is low, 1.5 m^2/KW(e) for single stage expansion and 1.0 m^2/KW(e) for multi-stage expansion (2 sided radiator). Specific mass is also very low, in the range of 0.5 to 1.0 kg/KW(e), depending on design, number of expansion stages, and type of metal construction. The SUSEE reactor is water-cooled and moderated using high enrichment U-235 fissile fuel in metla/UO_2 cermet plates similar to those employed for many years in many reactors around the World. The SUSEE turbine uses conventional steam turbine technology, except that the discharge pressure is substantially higher than customary, which reduces turbine size and weight. Details of the SUSEE reactor, power conversion, and radiator systems are described. Since SUSEE uses existing technology and the only new component, the zero g condensing radiator can be constructed and validated in a short time, e.g., 2 years. The SUSEE system could be developed for application well before the end of the decade. This plus its very low specific mass, make it a very attractive candidate for future space power systems.

Recent Developments in Vapor Core Reactors with MHD Power Conversion for Space Power Systems

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Very low specific-mass power generation in space is possible using Vapor Core Reactors with Magnetohydrodynamic (VCR/MHD) generator. These advanced reactors at the conceptual design level have potential for the generation of tens to hundreds of megawatts of power in space with specific mass of about 1 kg/kWe. Power for nuclear electric propulsion (NEP) is possible with almost direct power conditioning and coupling of the VCR/MHD power output to the VASIMR engine and a whole host of electric thrusters. The VCR/MHD based NEP system is designed to power space transportation systems that dramatically reduce the mission time for human exploration of the entire solar system or for aggressive long-term robotic missions. There are more than 40 years of experience in the evaluation of the scientific and technical feasibility of gas and vapor core reactor concepts. The proposed VCR is based on the concept of a cavity reactor made critical through the use of a reflector such as beryllium or beryllium oxide. Vapor fueled cavity reactors that are considered for NEP applications operate at maximum core center and wall temperatures of 4000 K and 1500K, respectively.

Advanced materials play a key role in the design and analysis of vapor core reactors and associated components. High temperature, high strength molybdenum alloys are important to the design of the reactor pressure vessel and radiator. Compatibility of molybdenum alloys with UF_4 has been demonstrated in experiments conducted at INSPI. They also provide adequate strength at the high temperatures encountered at the vessel wall and in other components. An ultra-high temperature radiator operating at a nominal 1500 K was designed based on earlier high temperature radiator designs. The current design employs molybdenum alloys for their high service temperature and compatibility with UF_4. A condensing radiator design is analyzed with cross heat pipes also of molybdenum alloy with attached carbon/graphite composite fins to provide the high thermal conductivity and high emissivity radiating surface.

A recent investigation has resulted in the conceptual design of a uranium tetrafluoride fueled vapor core reactor coupled to a MHD generator. Detailed neutronic design and cycle analyses have been performed to establish the operating design parameters for 10 to 200 MWe NEP systems. An integral system simulation code is developed to perform parametric analysis and design optimization studies for the VCR/MHD power system. Total system weight and size calculated based on existing technology has proven the feasibility of achieving exceptionally low specific mass (~1 kg/kWe) with a VCR/MHD powered system.

Discussions

Fission Thermal / Electric Propulsion

- Nuclear Isomers, Hill Roberts (SRS Technologies)
- Min-MagOrion: A Pulsed Nuclear Rocket for Crewed Solar System Exploration, Ralph Ewig and Dana Andrews (Andrews Space & Technology)
- Pulsed Magnetic Field Driven Gas Core Reactors for Space Power & Propulsion Applications, Samim Anghaie (U. of Florida) and Carey Butler (Institute for Scientific Research)

- NEMO: Exploration of Europa's Sub-Surface Ocean and Return of Samples to Earth Using Nuclear Propulsion, John Paniagua et al. (Plus Ultra Technologies)
- Nuclear Electric Systems Analyses and Technology Development Options for Outer Planet Missions, Benjamin Donahue (Boeing Phantom Works)
- SUSEE: An Ultra Lightwe ight Nuclear Electric Propulsion System Based on Existing Water Reactor and Steam Cycle Technology, James Powell et al. (Plus Ultra Technologies)
- Recent Developments in Vapor Core Reactors with MHD Power Conversion for Space Power Systems, Travis Knight and Samim Anghaie (U. of Florida)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

Technologies to Improve Ion Engine Performance, Life and Efficiency for NEP

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The performance of nuclear electric spacecraft critically depends on the ability of the electric propulsion system to reliably provide high specific impulse (*Isp*) thrust with great efficiency. Missions to the outer planets will require thrusters to operate for the order of ten years, several times the life of the state of the art NSTAR thruster. Propulsion system efficiency is a multiplying factor in the overall system efficiency "alpha", the determining parameter in how well a nuclear electric spacecraft performs on deep space missions. In order to help make nuclear electric propulsion systems a reality, at JPL we are, among other activities, developing models of the physical processes that control ion thruster performance, life and efficiency. We are using these models to aid in the design of advanced technology ion thrusters and thruster components that we are presently building and testing.

In this paper we present ion thruster design concepts created using the new computer codes that model performance limiting and erosion mechanisms. Presently, the codes model extraction grid ion optics and both discharge and neutralizer hollow cathodes.

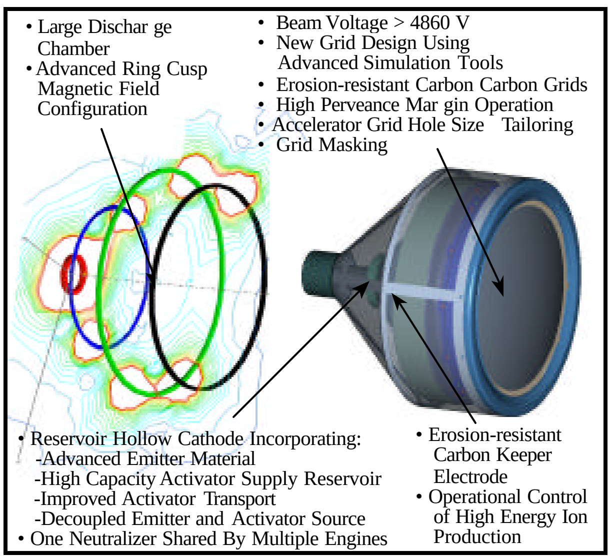

Figure 1. The Nuclear Electric Xenon Ion System (NEXIS) thruster includes new technologies needed for long life and high efficiency.

Work is underway on a thruster discharge chamber model. Basic plasma physical processes including ionization, electron transport, and charge exchange, are modeled in the codes. The grid ion optics and erosion model have been validated with NSTAR life test results, and are presently being applied to grid design in the In-Space Propulsion - Carbon Based Ion Optics program. The cathode models have been compared with data from the space station hollow cathode life test. As an example of the power of the computer models, we show how they are being used to design the Nuclear Electric Xenon Ion System (NEXIS) 7500 second *Isp* ion thruster for operation at 20kW (Figure 1).

Sputter Yield and Erosion Measurements For Ion Thruster Materials

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In this paper we describe a proposed future technique, as well as a technique that we currently use, to measure total and differential sputter yields of materials important to high specific impulse ion thrusters. The existing technique is based on a quartz crystal monitor that is swept at constant radial distance from a small target region where a high current density xenon ion beam is aimed. Differential sputtering yields were generally measured over a full 180° arc in a plane that included the beam centerline and the normal vector to the target surface. Sputter yield results are presented for a xenon ion energy range from 0.5 to 10 keV and an angle of incidence range from 0º to 70° from the target surface normal direction for targets consisting of molybdenum, titanium, solid (Poco) graphite, and flexible graphite (grafoil). Total sputter yields are calculated using a simple integration procedure and comparisons are made to sputter yields obtained from the literature. A discussion of the results is presented, including the observation of non-cosine behavior at low- and high-ion energies. Curve fits to the differential sputter yield data are provided. The results should prove useful to analysts interested in predicting the erosion profiles of ion thruster components and determining where the erosion products re-deposit.

We also discuss the proposed use as cavity ring- down spectroscopy (CRDS) for accelerated lifetime measurements. CRDS is an ultra-sensitive laser-based absorption technique that we intend to apply for measurements of plasma thruster erosion rates. The method directly yields eroded species concentration any may be used to infer information concerning the velocity and energy of eroded particles. The ultimate goal of such an approach would be to perform CRDS measurements on a particular electric propulsion device, and then use these values as inputs to a simple model that would estimate its expected lifetime, thus providing a methodology for performing accelerated lifetime tests. The synergism between electric propulsion system capabilities and mission definition is trending toward more demanding missions and a need for much greater thruster lifetimes. In the past, thrusters have been life tested over full mission profiles before they were launched. Thrust duration is, however, now at the point where required lifetimes are so great (several years of continuous operation) that this is no longer practical, and accelerated lifetime measurement procedures are needed. Preliminary calculations demonstrating the use of CRDS for this purpose are presented.

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High Power MPD Thruster Research at the NASA Glenn Research Center

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Interest in high power electromagnetic propulsion has been revived to support a wide range of demanding space missions, including orbit-raising for large commercial and military space platforms, propulsion for planetary cargo and piloted missions to support the NASA Human Exploration and Development of Space Strategic Enterprise, robotic deep space exploration missions, and potential interstellar precursor missions. Of the current electric propulsion options, electromagnetic thrusters can effectively process megawatts of power, providing a range of specific impulse values to meet the anticipated diversity of in-space propulsion requirements. To support these mission requirements, the NASA Glenn Research Center renewed its high power magnetoplasmadynamic (MPD) thruster research program in FY99. The current program encompasses advanced numerical modeling of self-field and applied-field MPD thrusters using the magnetohydrodynamic MACH2 code, and experimental testing of quasi-steady MW-class MPD thrusters in a high power pulsed thruster vacuum facility. This presentation provides an overview of the MACH2 code and recent simulation results, describes the pulsed thruster test facility, and presents initial performance data for high power self-field and applied-field gas-fed MPD thrusters operated in quasi-steady mode. Plans for future research are also presented.

Wave Generated Plasma Sources for Electric Propulsion

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A foray into developing compact helicon wave plasma sources has begun at Glenn Research Center. Interest and research into these devices spans a range of applications from small, electrodeless sources to be used with conventional ion or Hall engines to higher power, potentially high Isp thrusters using electron cyclotron resonance (ECR) heating to generate hot plasmas with no exposed electrodes. The small source seeks to benefit from the efficient production of high (10^{19} m^{-3}) density plasmas often demonstrated in helicon sources. An experimental version of this source has been constructed. The source consists of a water-cooled, 0.02 T applied field coil, a small (1.25 cm OD, 10 cm length) quartz discharge chamber, open at one end, and a simple copper strap loop antenna surrounding the quartz tube inside the magnet coil bore. The antenna is powered by a 300 W 13.56 MHz power supply. The dimensions of this small source depart markedly from standard helicon sources, which are generally long (~ 1 m) and thin. Plasma start up using the existing power supply has been limited by the low allowable reflected power limits on the device, and research has dealt with alternative ways to initiate plasma production. The latest results of this experimental effort will be reported

A theoretical/numerical effort to model the second, higher Isp concept indicates that the operating field strength and shape are critical factors in successful plasma wave heating. Recent results in the modeling of a conceptual ECR thruster using ray tracing show that a narrow source may provide a more effective thruster in terms of energy deposition and subsequent plasma expansion in a magnetic field. The initial findings of this study and their impact on thruster design will be presented. The uncertainties that remain for this concept – plasma generation, efficient ECR heating, maximum plasma temperature, and plasma detachment from a magnetic field – will be discussed.

Liquid-Metal-Fed Pulsed Plasma Thrusters

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Liquid metal propellants may provide a path toward more reliable and efficient pulsed plasma thrusters (PPTs). Conceptual thruster designs which eliminate the need for high current switches and propellant metering valves are described. Propellant loading techniques are suggested that, at least in principle, show promise to increase propellant utilization, dynamic, and electrical efficiency.

Experimental results from a prototype electromagnetically-pumped propellant feed system, and experiments in the initiation of arc discharges in liquid metal droplets, are presented.

Recent Advances in the Development of the VASIMR Engine

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The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is being developed to address requirements for fast, high-power interplanetary space transportation. Its electrodeless architecture relies on radio frequency (RF) waves to create and accelerate plasma in a magnetic nozzle. Progress on the physics and engineering of this concept continues along parallel paths and is the result of collaborations by a NASA-led research team, involving industry, academia and government facilities. Major physics accomplishments in 2002 include the characterization of the first stage helicon plasma source and the experimental demonstration of complete propellant burn up in both deuterium and helium. Major technology accomplishments include the demonstration of a thruster-relevant high temperature superconducting magnet prototype and development of a point design for a 1MW engine module. This presentation reports on these advances and presents plans for technology development.

An Experimental Investigation of Plasma Detachment from Magnetized Thruster Plumes

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An important issue in the successful operation of any thruster involving magnetized plasmas is whether or not the plume can detach from the magnetic fields as the thrust plume expands behind the spacecraft. This process must occur to a high degree of certainty in order that delicate spacecraft surfaces are not damaged by the thrust plumes over long periods of spaceflight. Since a number of emerging thruster technologies do rely on magnetic fields, it is imperative that the physics of detachment be well-understood.

Recent theoretical work has been directed at this question from two different perspectives: the breaking of adiabatic invariants in the plasma flow as the ion Larmor radii approach magnetic field scale lengths [1] and collective effects such as instabilities that may occur when the plasma flow exceeds the local Alfven speed [2]. Moreover, there are non-ideal effects, such as plasma viscosity, that may play an important role. Each of these phenomena can lead to detachment, shown theoretically, however they require quite different physical conditions to occur.

To this end we have assembled an experiment that is designed to address these questions experimentally. The plasma is created by a helicon source and is allowed to expand through a magnetic nozzle, in a manner similar to important thruster concepts now under study. The plasma expands into a large vacuum chamber where a suite of diagnostics is located to measure equilibrium plasma parameters as well as their fluctuation levels. We have taken care to insulate chamber walls in order to prevent line tying at the conducting surfaces. We shall summarize our findings to date and describe plans for a parametric study of detachment processes.

E. B. Hooper, J. Propulsion and Power, Vol. 9, No. 5, Sept. (1993)
B. Breizman, VASIMR Technical Review, Dec. (2002)

The Plasmoid Thruster Experiment (PTX)

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A plasmoid is a compact plasma structure with an integral magnetic field. Plasmoids, also called compact toroids, have been studied extensively in controlled fusion research, and are categorized according to the relative strength of the poloidal and toroidal magnetic field (B_p and B_t, respectively). An object with $B_p/B_t \gg 1$ is called a Field Reverse Configuration (FRC); if $B_p \approx B_t$, it is called a Spheromak. There are a number of possible advantages to using accelerated plasmoids for in-space propulsion. A thruster based on this concept would operate by repetitively producing plasmoids and ejecting them from the device at high velocity. The plasmoid is formed inside of a single turn conical theta-pinch coil; as this process is inductive, there are no life-limiting electrodes. Similar experiments have yielded plasmoid velocities of at least 50 km/s (1), and calculations indicate that velocities in excess of 100 km/s are possible. A thruster based on this concept would be capable of producing an I_{sp} in the range of 5,000 – 10,000 s, with thrust densities of order 10^5 N/m^2. The current experiment is designed to produce jet powers in the range of 5-10 kW, although the concept should be scalable to higher power. The purpose of this experiment is to determine the feasibility of this plasma propulsion concept. To accomplish this, it will be necessary to determine: a.) specific impulse and thrust, b.) efficiency and mass utilitization, c.) which type of plasmoid (FRC-like, or Spheromak-like) gives the best performance, and d.) the characteristics of actual thruster components (i.e., switch and capacitor technology). The plasmoid mass and velocity will be measured with a variety of diagnostics, including internal and external B-dot probes, flux loops, Langmuir probes, high-speed cameras, and an interferometer. Simulations of the plasmoid thruster using MOQUI, a time dependent MHD code, will be carried out concurrently with experimental testing. The PTX device is currently undergoing initial testing; preliminary experimental results are presented.

(1.) “Generation of poloidally rotating spheromaks by the conical theta pinch”, K. Kawai, Z.A. Pietrzyk, and H.T. Hunter, *Phys. Fluids* 30(8), August 1987, pgs. 2561-2568

Thrust Enhancement in the LAPPS Propulsion System*

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The ultrafast "laser Accelerated Plasma Propulsion System" LAPPS, makes use of lasers with very short pulse lengths to accelerate charged particles to relativistic speeds. Recent experimental data reveal that high intensity lasers are capable of producing collimated, charge-neutral proton beams containing more than $6x10^{14}$ particles at a mean energy of about 5 Mev with a total beam energy of 500J. If used in propulsion, these systems are capable of generating specific impulses of more than one million seconds, albeit at very modest thrusts, and require a nuclear power system to drive them. A major research effort at the University of Michigan is directed at finding ways to enhance the thrust of LAPPS. One approach is to irradiate larger focal spots in solid targets while varying laser intensity to study the interdependence of thrust and specific impulse. Using a one-dimensional analysis of ion acceleration by a laser-produced relativistic electron beam, we find that maximum ion velocity (hence specific impulse) scales directly with diameter-to-width (d/h) ratio of the beam giving rise to higher thrust and, simultaneously, to higher efficiency of energy transfer from the laser beam to the ejected particles. It is shown, for example, that an ion energy of about 10 Mev obtained when d ~ h can be increased forty fold if d=10 h. This also indicates that a two order of magnitude increase in the number of ejected particles will occur giving rise to a similar increase in the magnitude of thrust.

*Work supported by NASA Institute for Advanced Concepts (NIAC)

Discussions

Advanced Electric Propulsion - Thrusters

- Technologies to Improve Ion Engine Performance, Life and Efficiency for NEP, Ira Katz et al. (NASA JPL)
- Sputter Yield and Erosion Measurements For Ion Thruster Materials, Azer Yalin, John Williams, and Paul Wilbur (Colorado State U.)
- High Power MPD Thruster Research at the NASA Glenn Research Center, Michael R. LaPointe and James Gilland (Ohio Aerospace Institute)
- Wave Generated Plasma Sources for Electric Propulsion, Jim Gilland (Ohio Aerospace Institute)
- Liquid-Metal-Fed Pulsed Plasma Thrusters, T.E. Markusic (NASA MSFC)
- Recent Advances in the Development of the VASIMR Engine, Franklin R. Chang-Díaz et al. (NASA JSC)
- An Experimental Investigation of Plasma Detachment from Magnetized Thruster Plumes, M. E. Light and P. L. Colestock (LANL)
- The Plasmoid Thruster Experiment (PTX), Richard Eskridge et al. (NASA MSFC)
- Thrust Enhancement in the LAPPS Propulsion System, Terry Kammash (U. of Michigan)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

ASPW 2003 Summary Discussions

- Advanced Chemical and Earth-to-Orbit (ETO) Propulsion:
  - High-energy density material (HEDM) propellants, hybrids, detonation, etc.
  - Launch assist catapults (e.g., MagLev),
  - MHD-augmented chemical, virtual inlets, laser/microwave beamed energy, etc.
- Propulsion Component Improvements: Advanced materials, light-weight magnets, advanced radiators, etc.
- Beamed Energy Propulsion: Solar/laser/microwave thermal propulsion, high-power beamed-energy systems, etc.
- Propellantless Propulsion:
  - Solar/laser/microwave/plasma sails
  - Aero/gravity assist
  - Tethers, etc.
- Nuclear Propulsion:
  - Fission thermal, nuclear isomers
  - Fusion
  - Antimatter
- Advanced Electric Propulsion:
  - Fission thermal/electric/hybrid, NEP Power Systems
  - Thrusters (Ion, Hall, MPD, etc.)

Discussions (All)

- Objective is to determine where, in the area of future nuclear propulsion (and power) concepts, we would recommend that NASA funds be concentrated and why
- Primary Criteria: Cost and Safety, and Enabling New Missions

DISCUSSIONS

Mini-Workshop on Emerging Propulsion Technologies for Robotic Exploration of the Solar System (EPTW)
University of Alabama in Huntsville (UAH)
April 18, 2003

EPTW Technical Session on Emerging Technologies

- Brainstorming Session for TRL › 3 Technologies, John Cole, Facilitator (NASA MSFC)

EPTW Working Session on Emerging Technologies

- Schedule TBD